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THRUST VECTOR CONTROL SYSTEM STUDY FOR A LARGE LIQUID BOOSTER (U)

Daniel Stump, Capt, USAF

TECHNICAL REPORT AFRPL-TR-68-175

SEPTEMBER 1968

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6 THRUST VECTOR CONTROL SYSTEM STUDY
FOR A LARGE LIQUID BOOSTER (U). 8

9 Technical rept. 15 Mar - 15 May 68,

10 Daniel/Stump ~~Capt, USAF~~
Vernon/Olivier

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FOREWORD

(U) This report was prepared by Captain D. Stump, and Captain V. Olivier of the Solid Rocket Division, Air Force Rocket Propulsion Laboratory under project 305900[redacted]. The study was conducted as part of a joint effort with the Aerospace Corporation and SAMSO, Los Angeles to investigate the design characteristics of a typical low-cost liquid booster system.

(U) The study covers work conducted from 15 March to 15 May 1968. The manuscript was released by the author on 15 August 1968 for publication as a technical report.

(U) The author wishes to acknowledge the invaluable assistance of Mr. Lee F. Carter, Thiokol Chemical Corporation, Wasatch Division, and Captain Vernon Olivier, AFRPL, who helped the author find and properly input available data into the computer program used to evaluate the TVC Systems.

(U) This report contains no classified information extracted from other classified documents.

(U) Publication of this report does not constitute Air Force Approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

CHARLES R. COOKE
GS-15
Chief, Solid Rocket Division

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UNCLASSIFIED ABSTRACT

(U) This effort consisted of evaluating six thrust vector control systems for application on a Large Liquid Booster. The Thrust Vector Control Systems evaluated were Liquid Injection Thrust Vector Control, Hot-Gas Secondary-Injection Thrust Vector Control and the following four movable-nozzle thrust vector control systems: Flex-Seal Nozzle Thrust Vector Control (both Supersonic and Subsonic Seal), Ball and Socket Nozzle Thrust Vector Control and Gimbal Nozzle Thrust Vector Control. A pictorial representation of the TVC Systems investigated is shown in Figures 3, 4 and 5. The author used the "Advanced Thrust Vector Control Preliminary Design Computer Program" (AFRPL-TR-67-318) developed under AFRPL Contract AF04(611)-11647 with the Thiokol Chemical Corporation, to establish the preliminary Thrust Vector Control Systems Designs. The designs were then compared on the basis of Thrust Vector Control System performance (weight, envelope constraints, etc.). The effort consisted of three tasks. The first was the establishment of the baseline missile trajectory (point mass). The second was the use of the steering coefficients obtained from the baseline trajectory in conjunction with wind profiles, moments of inertia, center of gravity versus time and missile irregularities (C. G. offset, nozzle misalignments etc.) to obtain duty cycle requirements. The third task was the design of the Thrust Vector Control Systems of interest and a comparison of performance of the Thrust Vector Control System for each missile stage. For Stage I of the missile the Hot-Gas Secondary-Injection Thrust Vector Control System was the lightest system, with the Flex-Seal Nozzle Thrust Vector Control System second, and the Liquid Injection Thrust Vector Control System third. For Stage II the Flex-Seal Nozzle Thrust Vector Control System was lightest with the Hot-Gas Secondary-Injection Thrust Vector Control System second and the Liquid Injection Thrust Vector Control System third.

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TABLES

SECTION I

INTRODUCTION

(U) The objective of this effort was to evaluate the applicability of various Thrust Vector Control (TVC) Systems for the Low-Cost Liquid Booster. The "Advanced Thrust Vector Control Preliminary Design Computer Program" (AFRPL-TR-67-318) was used to design each TVC System. The resulting TVC Systems were evaluated primarily on the basis of TVC System weight. Cost comparisons were not conducted in this study.

SECTION II

TVC SYSTEM STUDY

(U) At the initiation of this study few of the required missile parameters were available. The missile was not defined other than by broad envelope and performance constraints. The basic missile design requirements are shown in Table III and the general missile profile is depicted in Figure 1.

(U) The AFRPL effort was divided into three interrelated tasks. The first task was to establish the baseline missile trajectory (point mass) to achieve the orbit defined in Table 1. The second task was to use the steering coefficients obtained from the trajectory run with wind profiles, moments of inertia, center of gravity versus time as well as missile irregularities (c. g. offset, nozzle misalignments, etc), to derive duty cycle requirements versus time necessary to actually accomplish the trajectory. The third task was the flying of the missile with each desired TVC system and compiling the data in an effort to compare the various TVC system performance characteristics.

(U) The Task I effort was accomplished by providing drag data in the form of axial coefficients versus mach number, as well as a flight-path description, to the trajectory subroutine of the computer program.

(C) Basically, the flight path of the missile consisted of a vertical rise to a velocity of 200 fps. At 200 feet per second (at T = 11.02 seconds) the missile would instantaneously attain a pitchover angle of 9.19663574 deg and fly this turn until T = 17.23 seconds. The missile would then

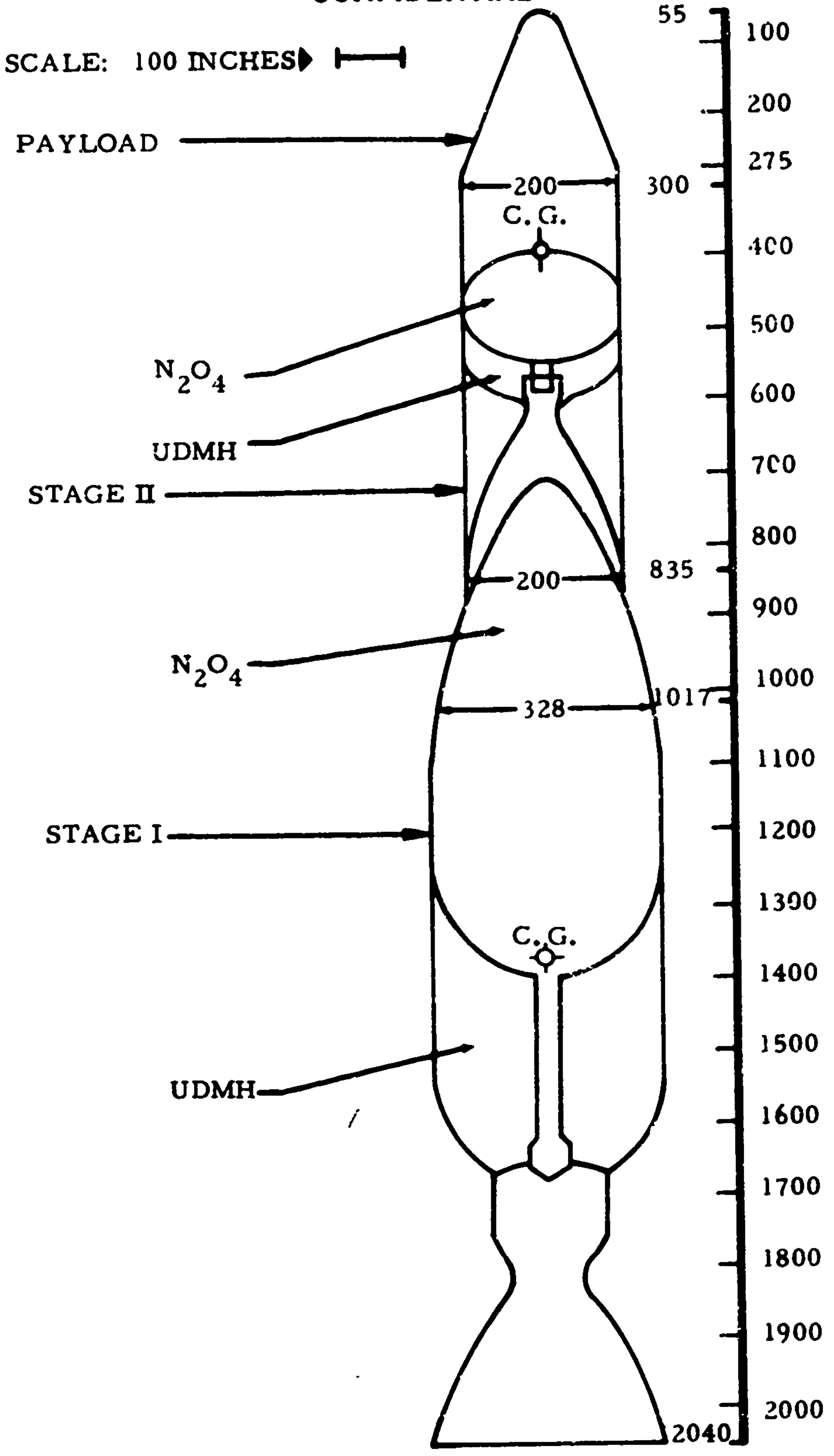


Figure 1. Low-Cost Liquid Booster Profile Payload

(C) Table I. Two-Stage MC/SLV - Design No. 3

MISSION		
Unmanned, 40,000 lbs Payload Weight, 80 naut. mi. Circular Orbit, 90 degrees Inclination		
VEHICLE DESIGN CONSTRAINTS		
930 psf Nominal, Dynamic Pressure Max Q		
4.5 g Maximum Axial Acceleration Max G		
1.5 Minimum Thrust To Weight Ratio At Lift-Off		
DESIGN CHARACTERISTICS*	STAGE I	STAGE II
Chamber Pressure, psia (MAX)	300	200
Specific Impulse at Equilibrium, Percent	90 ±1%	90 ±1%
Expansion Ratio	7	35
Specific Impulse, secs at S. L.	216	0
VAC.	270	306
Tank Design Pressures MAX; psia O	450	350
F	375 ±2%	275 ±2%
Propellant Mass Fraction	0.92	0.93
Engine Thrust, 10^6 lbs S. L.	3.749	- - -
VAC.	4.68[illegible] ±3%	0.340 ±3%
Usable Propellant Wt. 10^6 lbs	1.985	0.021
Engine Burn Time, sec.	132.5	247.9
Stage I Thrust Ideally Throttled to Meet Constraints of q_{max} And g_{max}		
Only Residual Engine Liner Weights Considered		
LITVC Injectant Assumed to Carry Own Weight		

* Result of Only Initial Cost-Optimization

fly a gravity turn to T = 150. 0 seconds with final burnout of Stage I. Stage II would ignite and Stage I would be jettisoned. At ignition of Stage II (at T = 153 seconds) a constant inertial pitch rate of 0.109086785 degrees per second down would be initiated. The pitchdown maneuver would last till burnout at T =380. 38 seconds and the 80-nautical-mile circular orbit would be achieved (Task I,80-nautical-mile circular orbit).

(U) The axial force coefficients for the missile were provided by the Aerospace Corporation, see Table II.

(C) Several trajectory runs were made before a satisfactory run was achieved. The major problems encountered were keeping within the maximum dynamic pressure (mas q=950 psi) and the maximum axial acceleration constraint (max=4. 5g). The above constraints were imposed to maintain propellant tank bulkhead integrity. To reduce max q and g to acceptable values, the thrust-to-weight ratio of the missile had to be reduced from 1. 5 to 1. 18. To retain the total impulse, the burn time of Stage I was extended from 132. 5 seconds to 153 seconds. The steering coefficeints used for the successful trajectory run were input into Task II.

(U) The Task II effort consisted of inputting the steering coefficients obtained from the successful trajectory run and the curves depicting the missile time variables. These variables include moments of inertia, center of gravity, weight, etc. The appendix shows the calculations and assumptions used to derive the time variables. Other required input data included outboard profile by body station, center of gravity offsets in the axial and side axis, nozzle angular misalignment, and nozzle throat offset, as well as wind profiles versus altitude. As with the trajectory runs, difficulty was experienced and several duty cycle runs were made before acceptable TVC duty cycle characteristics were obtained. It was found that the values assumed for wind profile had the greatest effect on a successful or unsuccessful flight of the missile. The assumed wind profile

Table II. Aerodynamic Drag Data

MACH NO.	AXIAL COEFFICIENT (C_A)
0.0	0.170
0.25	0.170
0.75	0.190
0.90	0.280
1.00	0.450
1.10	0.580
1.20	0.620
1.50	0.580
1.75	0.630
2.00	0.480
3.00	0.340
4.00	0.260
5.00	0.205
6.00	0.170

as depicted in Table III (A), which is considered realistic, resulted in the failure of the missile to attain its orbit. The final wind profile selected as shown in Table III (B) is not only reduced in magnitude by one-half, but where Table III (A) depicts the head wind condition, Table III (B) shows a tail wind actually assisting the missile in making its turning maneuvers.

(C) The original assumptions (missile irregularities) made for center of gravity (c. g.) offset, nozzle angular misalignment and nozzle throat offset (Figure 2) for the Stage I motor were: 6 inches, 0.025 degrees, and 0.25 inches, respectively. These parameters are shown in Table IV. The c. g offset value seemed realistic considering the size of the Stage I vehicle and the low-cost emphasis to be placed on the entire missile. The value of nozzle angular misalignment is rather optimistic and the value of nozzle throat offset might be optimistic. The numerical values given these parameters did not affect the missile attaining its orbit, but certainly would be expected to affect the TVC duty cycle characteristics and liquid injectant requirement output of the liquid injection TVC computer runs. Several alternative assumptions were made to determine the effect of specific assumptions on the duty cycle requirement and corresponding liquid injectant requirements. The alternative assumptions (Cases B, C and D) are shown in Table IV and at the bottom of Table VI are shown the corresponding weights of liquid injectant (UDMH) required The principal TVC duty cycle characteristics obtained from the assumptions discussed above are presented in Table IV, along with a description of the missile irregularity cases investigated. From Table IV one can see that the values given to the above-mentioned motor irregularities can have a profound effect on relative TVC system requirements.

(C) The previously mentioned "Successful trajectory and duty cycle run" should be further clarified. Although the 80-nautical-mile apogee was not achieved in either the Task I or II efforts, the successful run

Table III. Wind Profile Versus Altitude

A. HEADWIND	
Altitude - ft	Velocity - ft/sec
0.0	20.0
10,000.0	50.0
36,036.0	209.9
38,036.0	253.3
40,036.0	299.5
41,036.0	348.0
42,036.0	299.5
44,036.0	253.3
46,036.0	209.0
80,000.0	75.0
100,000.0	90.0

B. TAILWIND	
Altitude - ft	Velocity - ft/sec
0.0	10.0
10,000.0	25.0
36,036.0	104.9
38,036.0	126.6
40,036.0	149.7
41,036.0	174.0
42,036.0	149.7
44,036.0	126.6
46,036.0	104.9
80,000.0	37.5
100,000.0	45.0

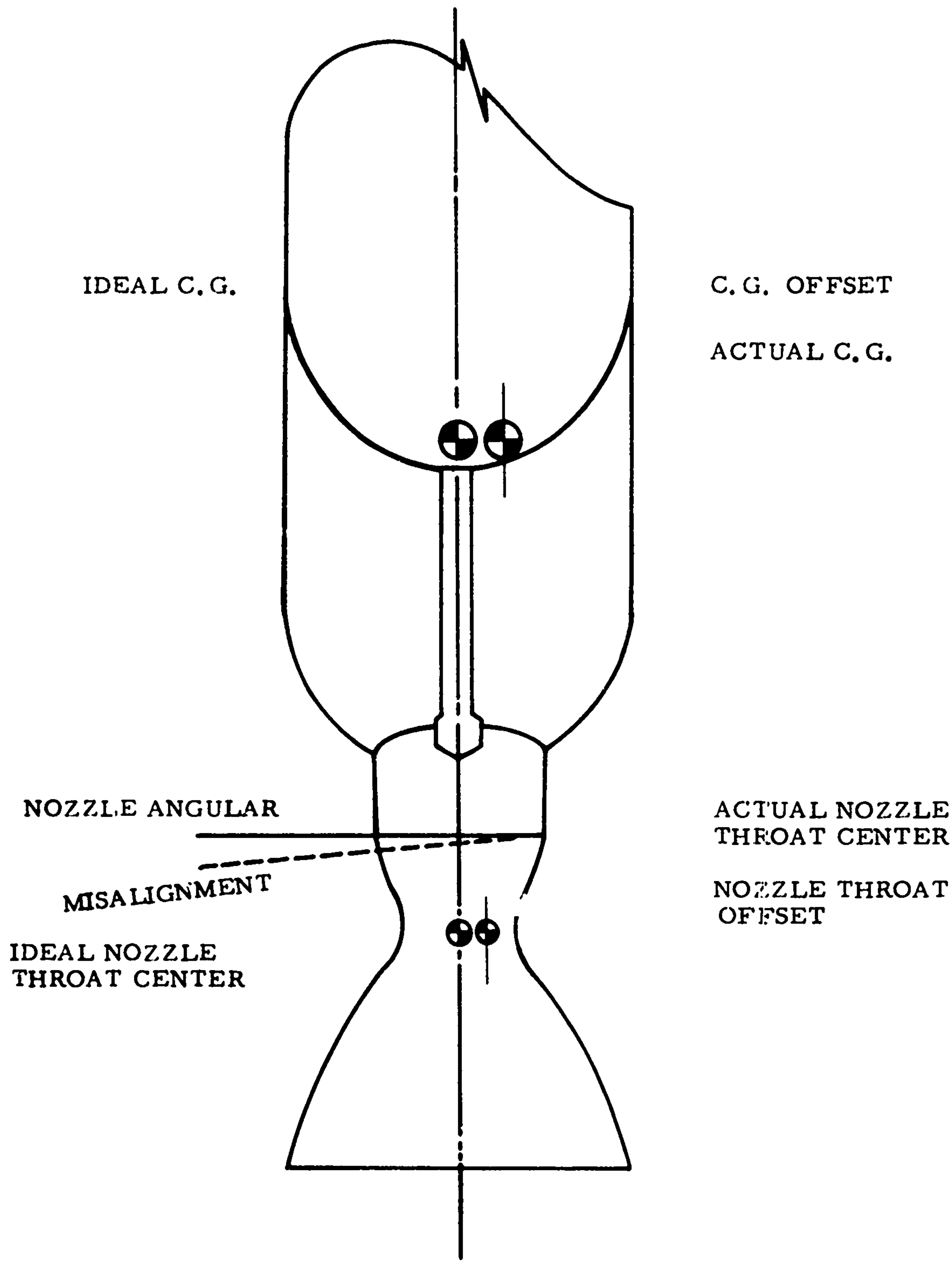


Figure 2. Illustration of Required Missile Irregularity Parameters

Table IV. TVC Duty Cycle Characteristics

	A	B	C	D
DESIGN THRUST VECTOR ANGLE, Deg	1.13	1.12	0.91	0.77
DESIGN SIDE LOAD, lbs	118,786	117,868	95,277	80,482
TVC SLEW RATE, Deg/sec	2.75	2.68	2.13	1.63
AVERAGE THRUST VECTOR ANGLE, Deg	0.548	0.550	0.338	0.177
MAXIMUM THRUST VECTOR ANGLE, Deg	1.133	1.125	0.909	0.768

MISSILE IRREGULARITY CASES			
	C.G. OFFSET (Inches)	NOZZLE ANGULAR MISALIGNMENT, Deg	THROAT OFFSET (Inches)
A	6.0	0.025	0.25
B	3.0	0.30	0.25
C	1.0	0.20	0.25
D	0.25	0.025	0.25

refers to a polar orbit of 76 nautical mile perigee and 81-nautical mile apogee. Given time, the precise orbit required could have been achieved by simply optimizing the thrust-weight ratio and the thrust-time trace of the missile by a trial and error method. This further optimization was not considered essential since the purpose of this study was simply to evaluate, relatively, the candidate TVC systems, not to obtain well-defined TVC systems.

(C) The Task III effort consisted of establishing TVC system performance data for the variety of TVC systems for evaluation (Figures 3, 4, 5). The TVC systems and cases investigated are shown in Table V. The first series of TVC system computer runs were made with the nozzle irregularities discussed above. The results of this series of computer runs are shown in Table VI. From Table VI, it is seen that for Stage I of the vehicle, the Hot-Gas Secondary-Injection System (5,778 lbs) is the most attractive TVC system, by weight, with the supersonic Flex-Seal Nozzle TVC System being intermediate at 11,544 pounds, and the Liquid Injection (UDMH) TVC System ranking third at 63,000 pounds.

(U) The Stage I HGSITVC System (Figure 3) consisted of a conventional (nonsubmerged) nozzle with externally ducted valves. (A more optimum nozzle for the HGSITVC System might have been a submerged nozzle with the valves mounted internally in the thrust chamber. However, the Aerospace Corporation directed that submerged nozzles would not be considered in these studies.) The TVC System consisted of 16 valves, (four valves per quadrant) positioned at an injection location of 0.4184 times the axial length of the nozzle (nozzle throat to exit plane) measured from the throat. The injection location was 25.231 degrees (perpendicular to nozzle wall at injection location.) The 16-valve configuration was chosen since the four-valves-per-quadrant configuration is the maximum number of valves per quadrant that can be input in the HGSITVC computer program subroutine. The optimum configuration resulting in the least weight

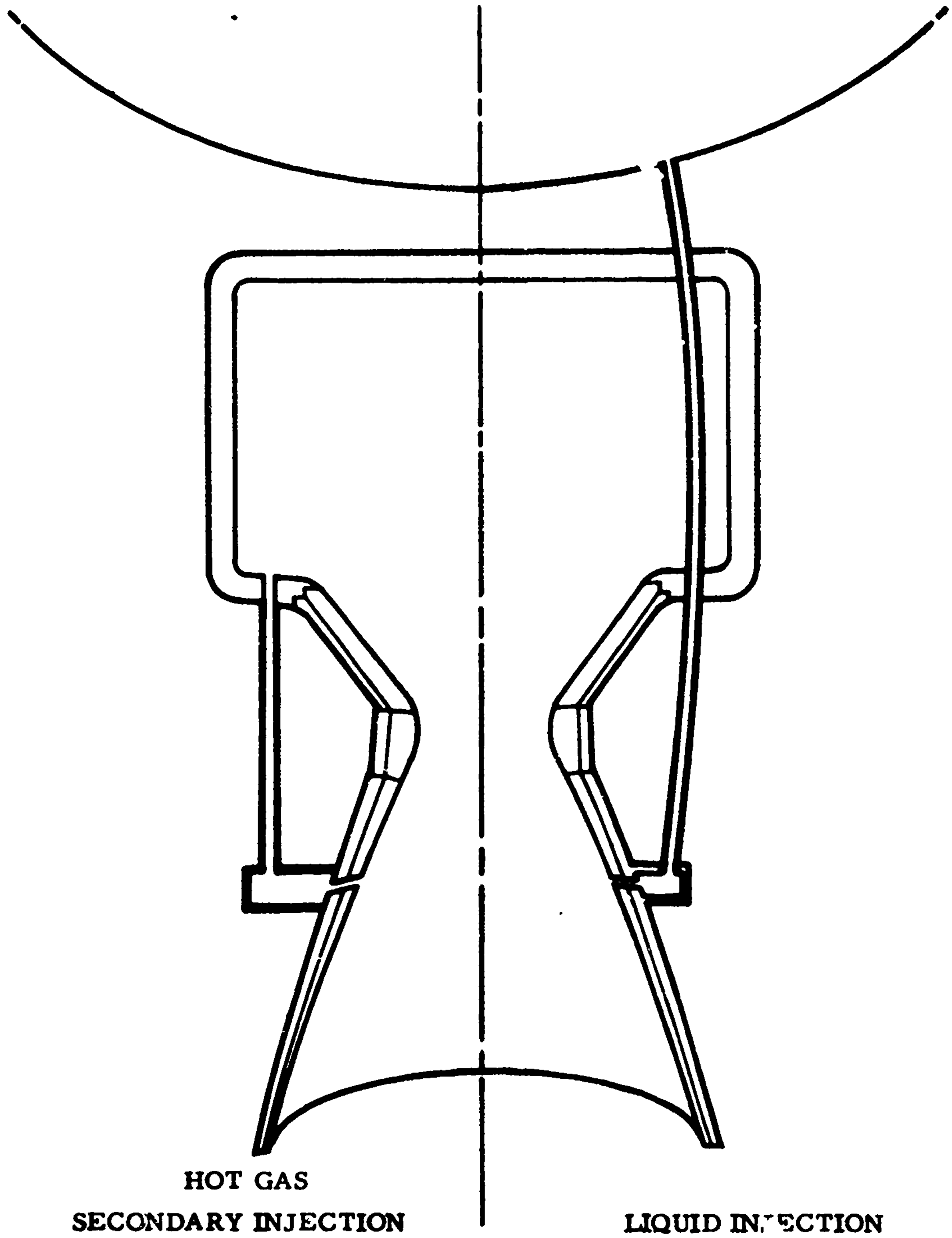


Figure 3. Schematic Illustration of Typical Injection Thrust Vector Control Systems

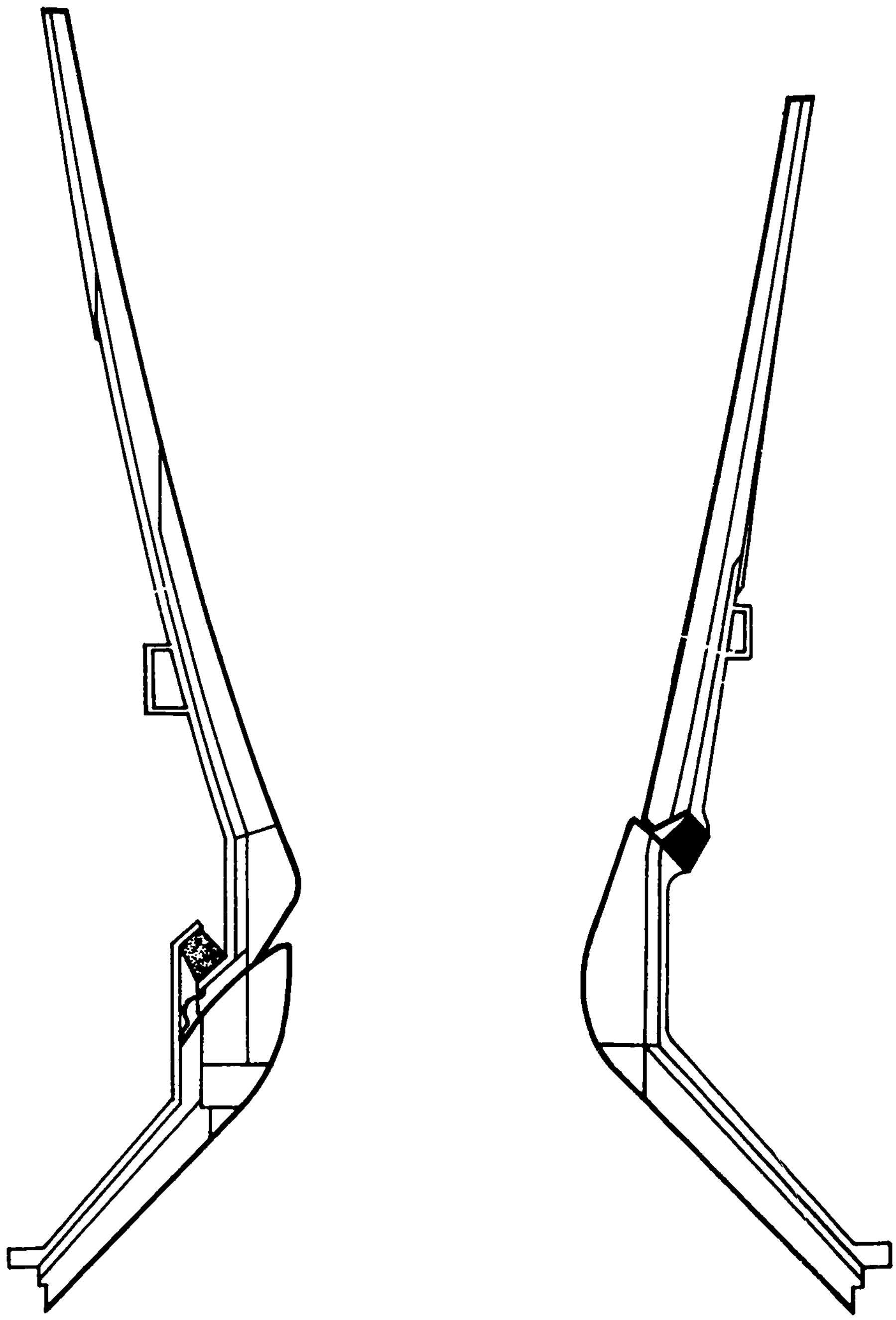


Figure 4. Typical Flex-Seal Nozzle Thrust Vector Control Systems

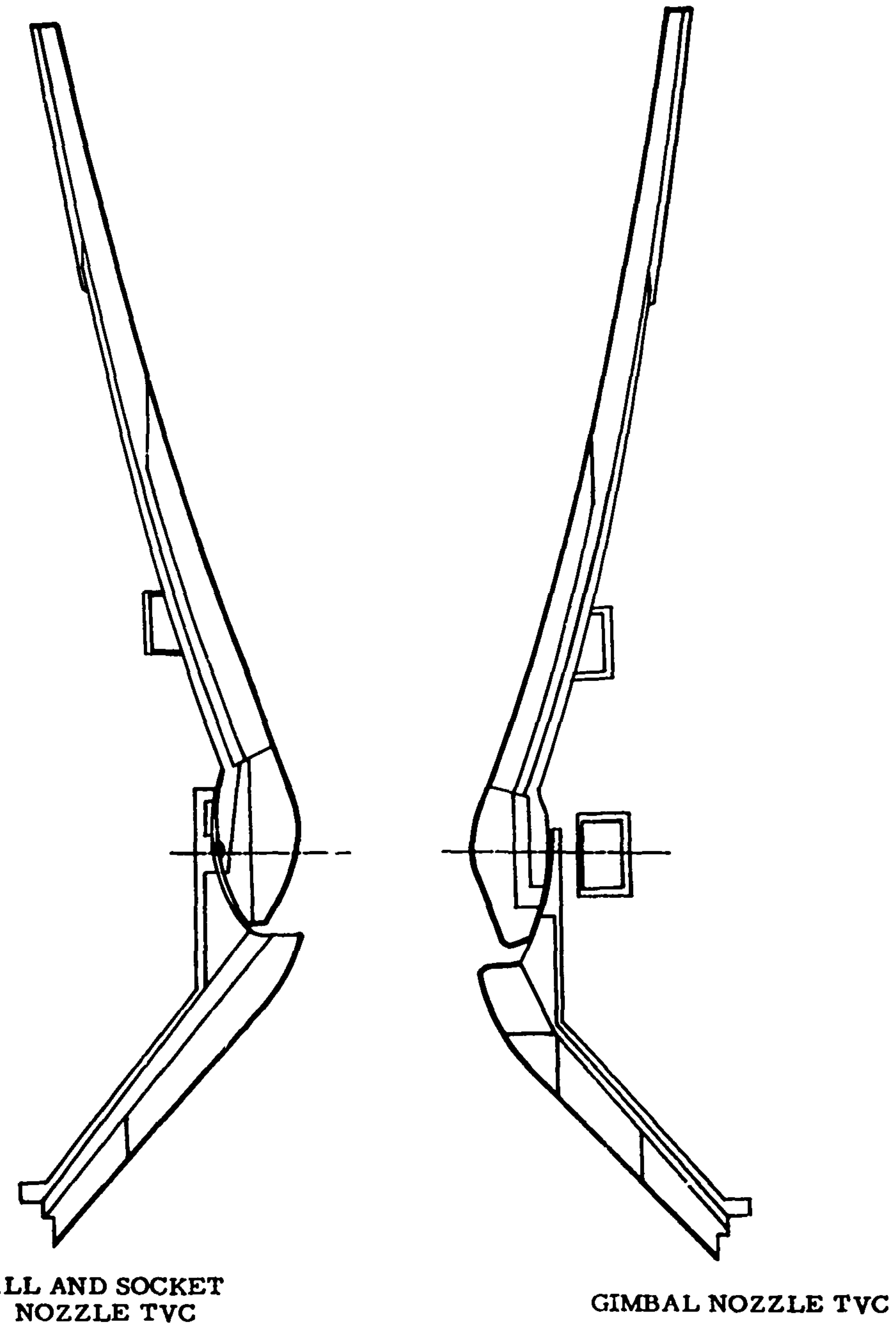


Figure 5. Typical Movable-Nozzle Thrust Vector Control Systems

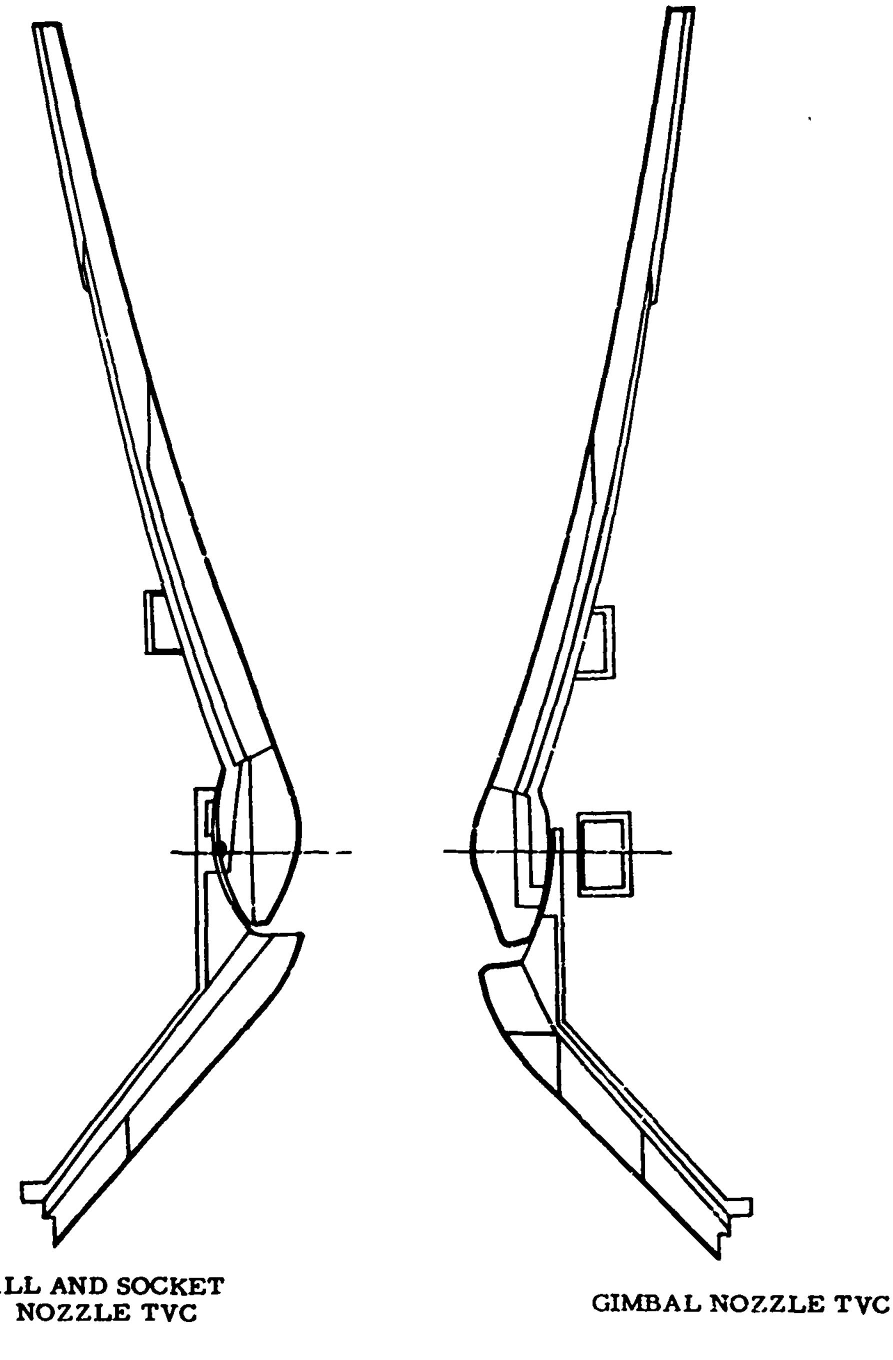


Figure 5. Typical Movable-Nozzle Thrust Vector Control Systems

Table V. TVC Systems Investigated

MISSILE IRREGULARITY CASE	A	B	C	D
Liquid Injection TVC (UDMH)	X	X	X	X
Liquid Injection TVC (NTO)*	X			
Hot-Gas Secondary-Injection TVC	X			
Flex-Seal Nozzle TVC (Supersonic)	X			
Flex-Seal Nozzle TVC (Subsonic)	X			
Ball and Socket Nozzle TVC	X			
Gimbal Nozzle TVC	X			

* Available for Stage I Only.

Table VI. TVC Systems Comparisons

CASE A: TVC System	TVC System Weight (lb)		Injectant Weight (lb)		Nozzle Structure (lb)		Nozzle Insulation (lb)		Flexible Bearing Assembly (lb)		Roll Control System (lb)		Nozzle TVC Roll (lb)	
	Stage I	Stage II	Stage I	Stage II	Stage I	Stage II	Stage I	Stage II	Stage I	Stage II	Stage I	Stage II	Stage I	Stage II
LITVC (UDMH)	63,000	8,427	50,179	6,889	14,888	3,270	16,340	6,424	N/A	N/A	5,261	760	100,690	19,173
LITVC (NTO)	28,326		20,736		14,888		16,340		N/A	N/A	5,261		66,016	
HGSITVC	5,778	4,334	N/A	N/A	14,528	4,132	11,195	3,645	N/A	N/A	6,409	760	38,975	13,059
Flex-Seal TVC Supersonic	11,544	1,189	N/A	N/A	23,707	2,860	13,168	3,028	9,833	623	6,409	760	46,060	8,024
Flex-Seal TVC Supersonic	13,271	1,358	N/A	N/A	29,521	3,453	20,425	3,875	11,872	869	6,409	760	70,691	9,594
Flex-Seal TVC Subsonic		1,409	N/A	N/A		3,881		2,730		705		760		8,972
Gimbal TVC	25,498	1,845	N/A	N/A	28,024	3,132	40,583	4,530	N/A	N/A	6,409	760	77,220	8,948
Ball and Socket	27,282	2,788	N/A	N/A	28,893	3,769	40,337	2,813	N/A	N/A	6,409	760	78,916	8,259
CASE B: LITVC (UDMH)	70,782		48,880		14,863		16,340		N/A		5,382		107,869	
CASE C: LITVC (UDMH)	43,685		29,777		14,246		16,340		N/A		4,907		80,380	
CASE D: LITVC (UDMH)	24,495		14,618		13,806		16,340		N/A		4,681		60,524	

HGSITVC System is a three-valve-per-quadrant system which would require larger mass-flow valve hardware. Since the HGSITVC System is the lightest weight system for Stage I, it should be noted that pintle valves capable of mass flows of 250 pound/second of chamber gas are not yet developed. The clean nature of the liquid propellant exhaust gas as well as the recent advances in ablative materials and the gains in technology of using various tungsten alloys would give optimism to such development efforts. The externally mounted, ducted pintle valves are similar in configuration to the Jet-Pipe type HGSITVC System that was dropped from solid rocket development programs approximately three years ago. At that time Jet-Pipe valve hardware was made of massive tungsten parts for which material properties were not available and little was known of proper design techniques. With present materials and design advances a Jet-Pipe type valve could be made to survive the Low-Cost Liquid Booster exhaust environment with a minimum of development effort.

(U) The Supersonic Flex-Seal Nozzle TVC System (Figure 4) was evaluated, although this particular Flex-Seal Nozzle Concept is still in the development stage. (Significant demonstration tests of a Supersonic Flex-Seal Nozzle - Contract F04611-68-C-0004 - will occur in November 1968 and February 1969.) The Subsonic Flex-Seal Nozzle TVC computer subroutine could not accommodate the hardware size required for the Stage I studies, although this routine did work for the Stage II studies. As can be seen from Table VI the Flex-Seal Nozzle TVC System weights for Stage II are very similar for both the Subsonic and Supersonic Seals. Since there is no reason to assume this similarity in system weights would vary appreciably for the Stage I configuration, the TVC System weight of a Subsonic Flex-Seal Nozzle TVC System for Stage I should be similar to the weight of the Supersonic Flex-Seal Nozzle TVC System. Since the Flex-Seal Nozzle TVC System was the second lightest TVC System for Stage I, it should be emphasized that the Flex-Seal Nozzle TVC System for Stage I would require approximately a 600-horsepower hydraulic

activation system. This actuation system is far beyond the largest flight-weight system ever demonstrated. Stage I of the Poseidon System only requires a 35-horsepower system. Studies are being conducted to determine the feasibility of replacing the hydraulic actuation systems for Flex-Seal Nozzles on large motors with a secondary TVC System that would actuate the primary TVC System. Even Stage II would require a 100-horsepower hydraulic actuation system to actuate the Flex-Seal Nozzle. It should further be emphasized that the Supersonic Flex-Seal Nozzle TVC computer subroutine was derived purely from extrapolation of the Subsonic Flex-Seal TVC routine performance curves. No analysis (aerodynamic, thermal, stress, cold flow, etc.) was conducted for the Supersonic Flex-Seal routine. From a present AFRPL Contract F04611-68-C-0004 (Flex-X) indications are that the torque requirements for the supersonic seal are one-half the requirement for a similarly sized subsonic Flex-Seal Nozzle. One should bear in mind, therefore, that the Supersonic Flex-Seal Nozzle TVC System designed by the present computer subroutine will be heavier than necessary. Under Contrac F04611-68-C-0004 a more accurate computer routine for the Supersonic Flex-Seal Nozzle TVC System will be incorporated into the existing computer program.

(C) The Stage I LITVC System consisted of thirty-six injector valves, (nine per quadrant). The injection location, as with the HGSITVC System, was 0.4184 times the axial length of the nozzle, measured from the throat, with an injection angle perpendicular to the nozzle axis. The nine-valve-per-quadrant LITVC System was the maximum number of valves per quadrant that could be input into the LITVC computer program subroutine. With the LITVC System, the optimum system (least weight) would be a four-valve-per-quadrant system. The injector valve mass flow would have been identical to present TITAN III injector valves if a 10-valve-per-quadrant TVC System had been designed.

(C) From Table VIII it is shown that for the LITVC System for Stage I, more than 50,000 pounds of injectant fluid is required, making the LITVC System relatively unattractive. The reason for the unusually large requirement for liquid injectant is the effect of the 6-inch c. g. offset on the duty cycle of the missile. During the entire Stage I flight an average thrust deflection angle of 0.55 degrees is required to overcome the effect of the 6-inch c. g. offset. If the requirement for injectant liquid is assumed to be 0.1 percent of the total impulse of the missile the Stage I requirement is 20,000 pounds of UDMH. This is based on the sophisticated TITAN III missile system. With the low-cost emphasis, as well as the non-aerospace industry fabrication planned for the Low-Cost Liquid Booster, it seems that the missile will require additional injectant to complete the duty cycle due solely to the looser tolerances (c. g. offset, nozzle misalignment, etc.) inherent with the fabrication criteria. Again, the TITAN III normally consumes only about 25 percent of the total available injectant liquid. The remainder of the injectant is "dumped" through the injector valves into the nozzle providing thrust augmentation. For the Low-Cost Liquid Booster it has been directed to assume that the injectant liquid (UDMH) will fly itself (i. e., the specific impulse of the UDMH will balance the weight penalty of the UDMH). This is certainly a misleading statement when we look at total missile performance. The UDMH will yield a specific impulse of approximately 130 to 150 seconds when it is dumped through the injector valves and its axial component will certainly provide a degree of thrust augmentation, but it will not approach the performance expected if an equal volume of propellant, UDMH/NTO (specific impulse 216 seconds), was burned and exhausted through the nozzle. The "dumping" of liquid injectant certainly does degrade total missile performance. The 36 injector valves (125-pounds-per-second mass flow) required for Stage I of the missile hardware and the increased complexity of the control systems due to the injectant liquid "dump" situation leads to additional sophistication of the propellant control systems.

(U) Shown in Table VII are representative breakouts of the two lightest weight Roll Control Systems for each stage.

(C) For Stage II the most attractive TVC System, again by weight, is the Supersonic Flex-Seal Nozzle TVC System (1,189 pounds). The Hot-Gas Secondary-Injection TVC System is second at 4,334 pounds and the Liquid Injection (UDMH) TVC System is third with 8,427 pounds.

(C) The Stage II HGSITVC System consisted of 16 (four per quadrant) externally mounted ducted pintle valves. The valve mass flow rate is 50 pounds per second. This size valve is well within valve design envelopes that have been successfully demonstrated. The valve injection location was 0.410 times the axial length of the nozzle (throat to exit plane) measured from the throat. The injection angle is 28.289 degrees (perpendicular to nozzle wall at injection location).

(C) The Stage II LITVC System consisted of 24 (six per quadrant) injector valves. The valve mass flow rate is 23 pounds per second. The valve size is well within production valve hardware size. The valve injection location was 0.240 times axial length of the nozzle, and the injection angle was 0.0 degrees (perpendicular to nozzle axis).

(C) After completion and evaluation of the first series of computer runs, the values of the missile irregularities were varied to dramatize the effect of these values on average vector angle requirement. The results of this effort are also shown in Table VI. From Table VI, it can be seen that when the missile c.g. offset is reduced to 0.25 inch, and the nozzle angular misalignment to 0.025 inch, the average duty cycle vector angle is reduced to 0.1767 degrees and the liquid injection TVC injectant fluid requirement is reduced to approximately 15,000 pounds. These results demonstrate the overbearing effect of missile irregularities on missile performance and TVC system requirements. Table VI shows the TVC

Table VII. Roll Control System Weight Breakdown

Dual Warm-Gas Generator:	STAGE I	STAGE II
Weight of Dual Generator Warm-Gas System	6,409.30 lbs	760.96 lbs
Weight of Dual Generator Grain	1,624.66 lbs	191.41 lbs
Weight of Dual Generator Grain and Case	2,850.28 lbs	335.81 lbs
Weight of Dual Generator Relief Valve	43.69 lbs	5.91 lbs
Weight of Thruster	19.35 lbs	4.18 lbs
Weight of Warm-Gas Lines	289.74 lbs	29.57 lbs
Gas Generator Pressure	2,500.00 psi	2,500.00 psi
Dual Generator Flow Rate	10.15 lb/sec	0.751 lb/sec
Nozzle Flow at 1000 psi	4.062 lb/sec	0.300 lb/sec
Length of Warm-Gas Lines	515.2 in	314.2 in
Wall Thickness of Warm-Gas Lines	0.2 in	0.1 in
Outside Diameter of Warm-Gas Lines	5.1 in	1.6 in
Dual Cold-Gas System:	**STAGE I**	**STAGE II**
Weight of Dual-Tank Cold-Gas System	10,286.26 lbs	1,233.11 lbs
Weight of Gas Used Per Nozzle	984.34 lbs	117.95 lbs
Weight of Residual Gas in Dual Tank	495.54 lbs	59.50 lbs
Weight of Gas on Board	2,961.52 lbs	354.89 lbs
Weight of Dual Tank	3,148.52 lbs	377.26 lbs
Weight of Lines and Fittings	71.89 lbs	5.96 lbs
Weight of Thruster	44.17 lbs	3.80 lbs
Weight of Dual Tank Regulator	2.00 lbs	2.00 lbs
Initial Tank Pressure	6,000.0 psi	6,000.0 psi
Regulator Output Pressure	750.0 psi	750.0 psi
Final Tank Pressure	900.0 psi	900.0 psi
Dual Tank Flow Rate (Initial)	28.606 lb/sec	2.115 lb/sec
Volume of Dual Tank	112,236.1 in	13,448.4 in
Dual Tank Wall Thickness	1.133 in	0.558 in
Outside Diameter of Gas Lines	2.453 in	0.820 in
Wall Thickness of Gas Lines	0.049 in	0.020 in
Length of Gas Lines	515.2 in	314.2 in

duty cycle characteristics as well as the LITVC System comparison for the four sets of motor irregularities studied. Unfortunately, time did not permit the rerun of all the candidate TVC systems evaluated under the first series of Task III.

SECTION III

CONCLUSIONS AND RECOMMENDATIONS

(U) For Stage I of the missile the Hot-Gas Secondary-Injection Thrust Vector Control (HGSITVC) System was the lightest system with the Supersonic Flex-Seal Nozzle TVC System second and the Liquid Injection TVC (LITVC) System (UDMH) third. For Stage II the Supersonic Flex-Seal Nozzle TVC System was lightest, the Subsonic Flex-Seal Nozzle TVC System was second, the HGSITVC System third and the LITVC System (UDMH) was fourth.

(U) For the HGSITVC System the large flow-rate injector valves for Stage I need to be developed.

(U) For the Flex-Seal Nozzle TVC System, the major development task is the high-horsepower actuation system required.

(U) The LITVC System would require a minor amount of development for the Stage I injector valves.

(U) For Stage II the HGSITVC injector valves are well within the envelope of demonstrated hardware and the LITVC injector valves are within the envelope of production hardware.

(U) The values of missile irregularities (c. g. offset, nozzle misalignment, etc.) have a profound effect on missile duty cycle requirements which in turn directly influence TVC System requirements, particularly TVC Systems such as HGSITVC and LITVC.

(U) For HGSITVC Systems the optimum (weight) system consists of three valves per quadrant. The fewer the valves the larger the mass flow required per valve, and as with Stage I (250-pound-per-second valve) the greater the need for development work. The larger the number of valves the greater the cost of the TVC System.

(U) For LITVC Systems the optimum (weight) system is a four-valve-per-quadrant system. In an effort to use TITAN III injector valve hardware a 10-vavle-per-quadrant system is required which will add weight and certainly increase cost of the LITVC System.

(U) It is recommended that future TVC System Studies be conducted for the Low-Cost Liquid Booster when more definite missile parameters become available. The new Supersonic Flex-Seal Nozzle TVC System Computer subroutine being developed under Contract F04611-68-C-0004 should be used for future TVC studies. The TVC System Designs resulting from the new subroutine should indicate that the Supersonic Flex-Seal Nozzle Designs are lighter and require a far less powerful actuation system.

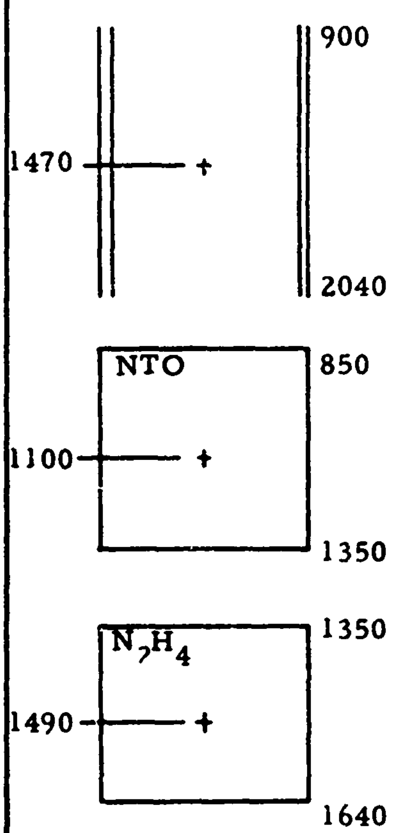
APPENDIX

DOCUMENTATION OF INPUT DATA, INCLUDING STEERING COEFFICIENTS AND MISSILE TIME PARAMETERS

APPENDIX

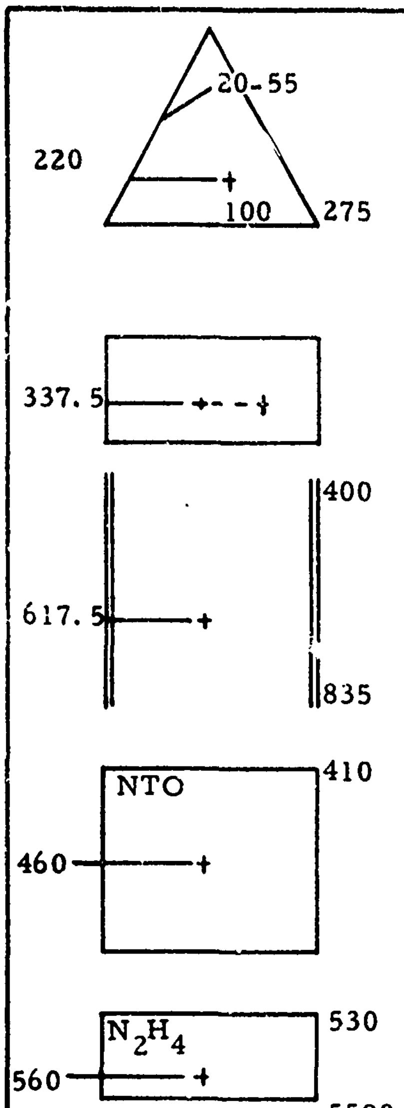
DOCUMENTATION OF INPUT DATA, INCLUDING STEERING COEFFICIENTS AND MISSILE TIME PARAMETERS

TABLE VIII. Stage I - Summary of Input Data



B. S. (X_{cg} In)	Wt (Lb)	I_{yy} (slug-ft^2)
1470	197,120	5,179,942
1100	1,638,000	9,742,794
1490	628,880	1,799,518

Table IX. Stage II and Payload



B.S. X_{cg} (In.)	Wt (Lb)	I_{yy} (Slug-ft^2)
220	8,710	5,650
337.5	32,250	27,200
617.5	21,000	94,137
460	209,000	176,307
560	70,000	40,920

X_{cg} (Stage II and Payload Loaded) = 472.12 in.

WT (Stage II and Payload Loaded) = 341,960 lb

I_{yy} (Stage II and Payload Loaded) = 812,882 slug-ft^2

Tabl^r X. Calculation of C. G. and Moment of Inertia

STAGE I IGNITION

$$X_{cg} = \frac{\Sigma(\text{WT.} \times X_{cg})}{\Sigma \text{WT.}}$$

$$= \frac{(539,080 \times 838.9) + (1,638,000 \times 1100) + (628,880 \times 1490)}{539,080 + 1,638,000 + 628,880}$$

$$= 1137.4 \text{ inches}$$

$$I_{yy} = \Sigma I_{yy} + \Sigma\left[\frac{\text{WT.}}{32.17} \quad \frac{(X_{cg} - X_{cg_o})^2}{144}\right]$$

$$= 32,867,834 + 9,742,794 + 1,799,518$$

$$+ \frac{539,080}{32.174} (1137.4 - 838.91)^2 \frac{1}{144}$$

$$+ \frac{1,638,000}{32.174} (1137.4 - 1100)^2 \frac{1}{144}$$

$$+ \frac{628,880}{32.174} (1490 - 1137.4)^2 \frac{1}{144}$$

$$= 72,147,989 \text{ slug - ft}^2$$

STAGE I IGNITION WEIGHT = 2, 805, 956 lb

Table X. (Continued)

STAGE I BURNOUT

$$X_{cg} = \frac{\Sigma(WT. \times X_{cg})}{\Sigma WT.}$$

$$= \frac{(341,960 \times 472.12) + (197,120 \times 1470)}{341,960 + 197,120}$$

$$= 838.91 \text{ inches}$$

****

$$I_{yy} = \Sigma I_{yy} + \Sigma\left[\frac{WT.}{32.174} \frac{(X_{cg} - X_{cg_o})^2}{144}\right]$$

$$= 812,882 + 5,179,942$$

$$+ \frac{341,960}{32.174}(838.9 - 472.12)^2 \frac{1}{144}$$

$$+ \frac{197,120}{32.174}(1470 - 838.9)^2 \frac{1}{144}$$

$$= 32,867,834 \text{ slug - ft}^2$$

****

STAGE I BURNOUT WEIGHT = 539,076 lb

Table X. (Continued)

STAGE II IGNITION

$$X_{cg} = \frac{\Sigma(\text{WT.} \times X_{cg})}{\Sigma \text{WT.}}$$

$$= \frac{(62,960 \times 414.64) + (209,000 \times 460) + (70,000 \times 560)}{62,960 + 209,000 + 70,000}$$

$$= 472.12 \text{ inches}$$

****

$$I_{yy} = \Sigma I_{yy} + \Sigma\left[\frac{\text{WT.}}{32.174} \frac{(X_{cg} - X_{cg_0})^2}{144}\right]$$

$$= 427,442.8 + 176,307 + 40,920$$

$$+ \frac{62,960}{32.174} (472.1 - 414)^2 \frac{1}{144}$$

$$+ \frac{209,000}{32.174} (472.1 - 460)^2 \frac{1}{144}$$

$$+ \frac{70,000}{32.174} (560 - 472.1)^2 \frac{1}{144}$$

$$= 812,882 \text{ slug - ft}^2$$

****

STAGE II IGNITION WEIGHT = 341,960 lb

Table X. (Continued)

STAGE II BURNOUT

$$X_{cg} = \frac{\Sigma(WT. \times X_{cg})}{\Sigma WT.}$$

$$= \frac{(8,710 \times 220) + (33,250 \times 337.5) + (21,000 \times 617.5)}{8,710 + 33,250 + 21,000}$$

$$= 414.64 \text{ inches}$$

****

$$I_{yy} = \Sigma I_{yy} + \Sigma\left[\frac{WT.}{32.174} \quad \frac{(X_{cg} - X_{cg_o})^2}{144}\right]$$

$$= 5,650 + 27,200 + 94,137$$

$$+ \frac{8,710}{32.174} (414.64 - 220)^2 \frac{1}{144}$$

$$+ \frac{33,250}{32.174} (414.64 - 337.5)^2 \frac{1}{144}$$

$$+ \frac{21,000}{32.174} (618.5 - 414.64)^2 \frac{1}{144}$$

$$= 427,442.8 \text{ slug - ft}^2$$

****

STAGE II BURNOUT WEIGHT = 62,960 lb

(U) Using the preceding determinations of weight, X_{cg} and I_{yy} at ignition and burnout, a curve was constructed of these parameters throughout the burn duration, based on typical characteristics of operational motors. These curves (Figures 6 and 7) were then used to generate the input for the computer program. This procedure is crude, but should be satisfactory for this preliminary study.

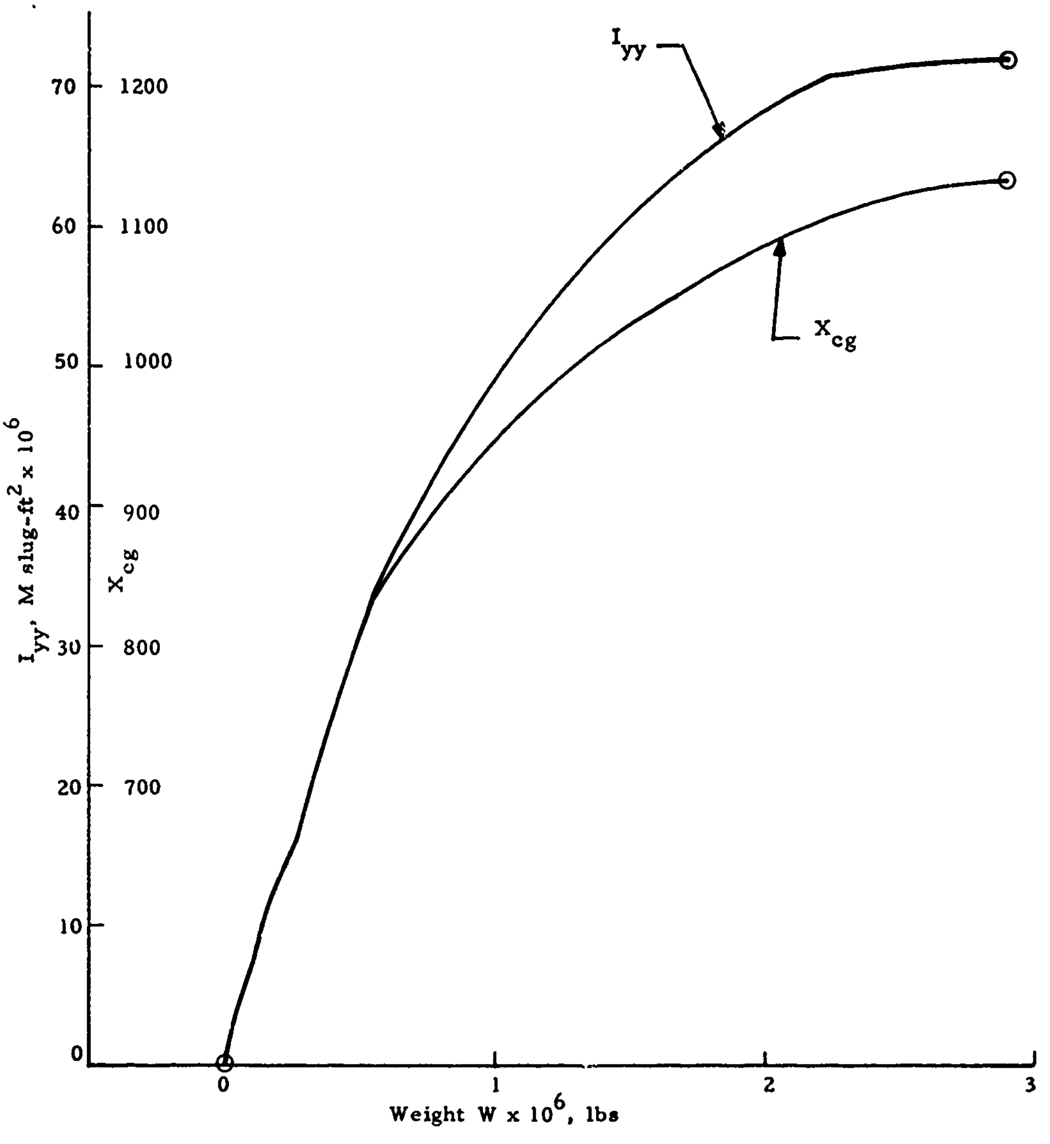


Figure 6. Stage I - C. G. and I_{yy} Variation with Burn Time

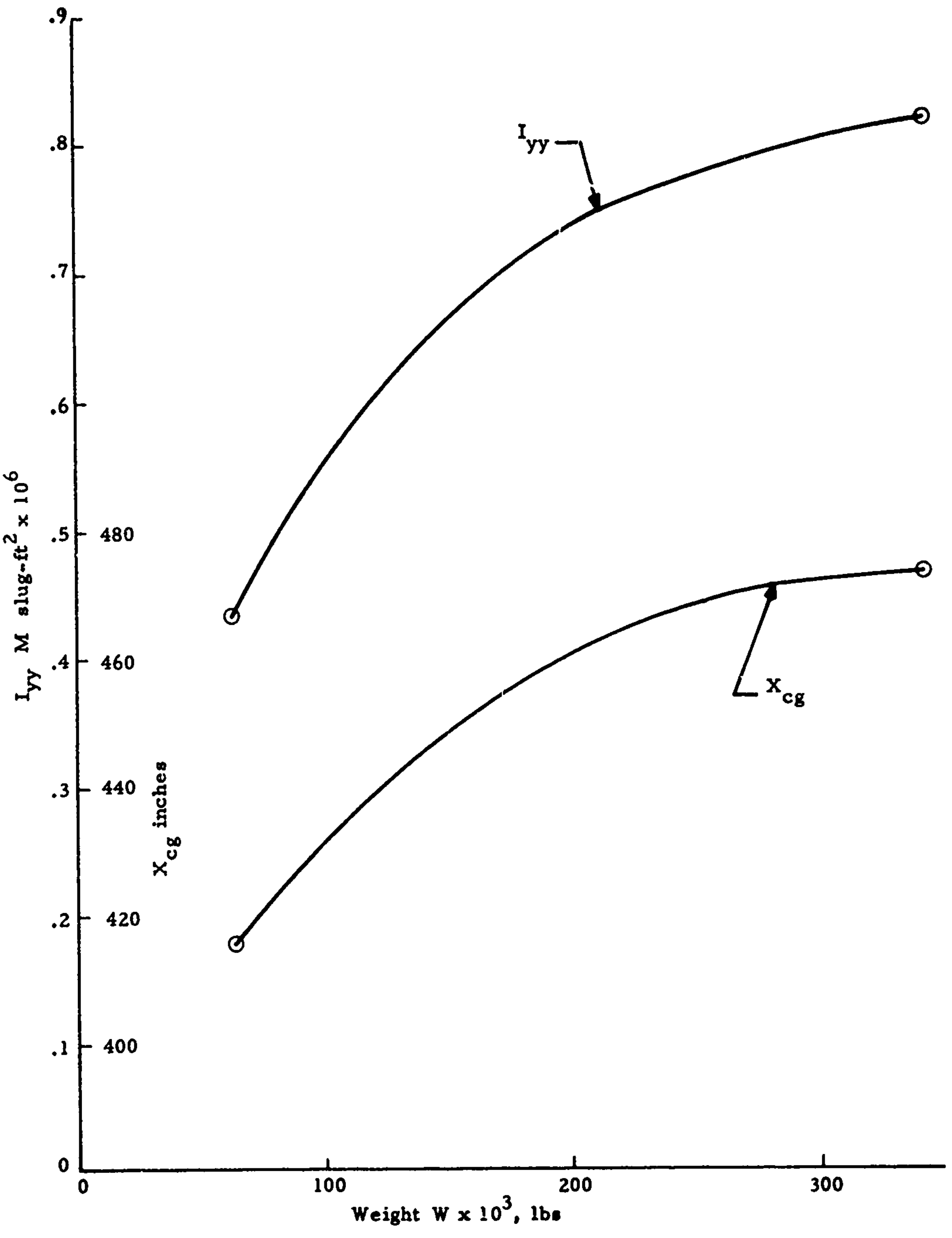


Figure 7. Stage II - C. G. and I_{yy} Variation with Burn Time

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13. ABSTRACT

(U) This effort consisted of evaluating six thrust vector control systems for application on a Large Liquid Booster. The Thrust Vector Control Systems evaluated were Liquid Injection Thrust Vector Control, Hot Gas Secondary Injection Thrust Vector Control and the following four movable nozzle thrust vector control systems; Flex-Seal Nozzle Thrust Vector Control (both Supersonic and Subsonic Seal), Ball and Socket Nozzle Thrust Vector Control and Gimbal Nozzle Thrust Vector Control. The author used the "Advanced Thrust Vector Control Preliminary Design Computer Program" (AFRPL-TR-67-318) developed under AFRPL Contract AF04(611)-11647 with the Thiokol Chemical Corporation, to establish the preliminary Thrust Vector Control Systems Designs. The designs were ~~then~~ compared on the basis of Thrust Vector Control System performance (weight, envelope constraints, etc.) The effort consisted of three tasks. The first was the establishment of the baseline missile trajectory (point mass). The second was the use of the steering coefficients obtained from the baseline trajectory in conjuction with wind profiles, moments of inertia, center of gravity versus time and missile irregularities (C.G. offset, nozzle misalignments, etc.) to obtain duty cycle requirements. The third task was the design of the Thrust Vector Control Systems of interest and a comparison of performance of the Thrust Vector Control System for each missile stage. For Stage I of the missile the Hot Gas Secondary Injection Thrust Vector Control System was the lightest system, with the Flex-Seal Nozzle Thrust Vector Control System second, and the Liquid Injection Thrust Vector Control System third. For Stage II the Flex-Seal Nozzle Thrust Vector Control System was lightest with the Hot Gas Secondary Injection Thrust Vector Control System second and the Liquid Injection Thrust Vector Control System third.

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14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Large Booster						
Liquid Rocket Engine						
Thrust Vector Control System						
Liquid Injection TVC						
Movable Nozzle						
Flex-Seal Nozzle						
Hot-gas Valve						
Gimbal Nozzle						
TVC System Design						

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